Structural Optimization in Vehicle Development

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Abstract
This paper presents an overview of structural optimization and some closely related subjects in the automobile industry. An historical review of the development of structural optimization is given. Some of the fundamental steps which were taken and the nature of the problems that had to be overcome will be highlighted. The current state of technical affairs relating to the optimizer algorithms, analysis and pre/post processing is reviewed, considering theoretical as well as application oriented aspects. Finally, the application of structural optimization during the development process of an automobile is discussed, including identification of its major benefits. Examples and case studies will demonstrate the applicability and limitations of structural optimization in daily engineering practice. The paper ends with a review of future trends in structural optimization applications and their implications.

1. Introduction

A structure is a collection of physical components arranged and supported in such a manner to carry loads. In the automotive sense, the primary load bearing structure is the vehicle body and its suspension system. An encyclopaedia definition of the word optimization revealed: "A mathematical technique for finding the maximum or minimum value of a function of several variables subject to functional constraints". The same encyclopaedia also presented the following definition: "making the best of anything". Applied to vehicle structural design optimization, this paper thus addresses the methods of designing the best vehicle body and suspension system. The requirement, for example, to reduce body weight by making structural design modifications is associated with the quest for better fuel efficiency. Constraints on the designer include strength, durability, crash, handling, and comfort performance.

This paper presents an historical review of the evolution of structural optimization and discusses structural optimization methods generally. These methods evolved in the late 1950´s, primarily in the aerospace industry, where the need to design lightweight structures is critical. The combination of advances in different fields characterizes this evolution process. Advances in mathematics (operations research), structural analysis methods (matrix methods), computer sciences, and, in particular, the adoption of so-called approximate analysis models were required to arrive at the current state of affairs in applied structural optimization. A review of the current methods routinely used in structural optimization in the automotive industry is presented. These methods are primarily iterative schemes in which gradient-based optimization algorithms are applied to high quality approximate analysis models. Typical analysis disciplines are discussed.

The review of current methods is supported by the presentation of some successful applications of structural design optimization in the automotive industry. These examples highlight the optimization of NVH (noise, vibration and harshness) performance for a luxury class vehicle. The examples illustrate the enormous demands that these methods make on the currently available computational resources.

Applications of structural optimization today in their infancy – such as shape, discrete variable and topology optimization – represent difficult problems and require different methods. These topics are discussed in an outlook to the future of the methods and applications in the field of structural optimization in the automotive industry. Particular reference is made to NVH analysis, which is characterized by the demand for improved sound and vibration comfort. Obviously, such prognosis is necessarily speculative. However, it is likely that the future search for global optimum in large scale multiple analysis discipline structural design problems will require evolutionary algorithms and very intelligent reductions of the design space.

The conclusion includes some of the author's personal and philosophical thoughts on the value of structural optimization in the automotive industry, and suggestions for improving the processes to take full advantage of the currently available optimization technology.

2. Review of History

The modern methods used in structural optimization evolved in the late 1950's, primarily in the aerospace industry, where the need to design lightweight structures is critical. The combination of advances in different fields characterizes this evolution process. Advances in mathematics (operations research) led to the mathematical programming techniques at the heart of the optimization algorithms. Parallel research on fully stressed and optimality criteria methods provided the necessary spirit of competition in the academic research community. Advances in structural analysis methods (matrix methods) and computer sciences and, in particular, the adoption of so-called approximate analysis models, were required to arrive at the current state of affairs in applied structural optimization.

It will be useful to review some definitions to facilitate an understanding of structural optimization concepts. In this context, a structure is described by an idealized model that is abstract and symbolic. This model is characterized by a finite set of quantities that specify materials, the arrangement and dimensions of the structure, the loading conditions and manner in which the structure is supported. The term loading conditions refers to a set of mechanical loads that approximately represent the effect of the environment on the structure to which it is exposed in its operative design condition. Responses are defined to be effects which the loading causes and whose quantities are used to characterize the behavior of the structure. Design variables are those parameters defining a structural system that are varied within prescribed limits by the design modification procedure. A design is characterized by a set of pre-assigned parameters and design variables. Constraints are functions of the design variables whose value must be equal to or less than some prescribed value. An objective function is some function of the design variables which provides the designer with a basis for judgment of acceptable designs. Typically, weight is the selected objective function, although this is not a requirement. A design is considered feasible if it does not violate any constraint. An optimum design is a design that yields a minimum value of the objective function in the design space associated with the allowable range of the design variables. Analysis is the procedure by which the behavior of the structure is determined.

Minimum weight optimum design of aircraft structural components was initially developed during World War II. By 1958, both Stanley and Gerard had published books dealing primarily with the minimum weight optimum design of aircraft components. The basic approach followed in this early work can be characterized as "simultaneous failure mode design optimization method" where a structural component is sized in a manner that several selected modes of failure become critical simultaneously. Setting the number of failure modes equal to the number of independent design variables converted the design optimization problem from an inequality constrained weight minimization problem to a set of non-linear differential equations. The success of these methods depended on sound intuition and good physical insight to guide the selection of the correct set of critical constraints. For aircraft components such as columns and stiffened panels subject to a single loading condition the "simultaneous failure mode design optimization method" led to a set of constraint equations which could often be solved explicitly for the design variable values. These values frequently corresponded to the minimum weight optimum design and they were commonly expressed as functions of some measure of the loading intensity; force over length squared for a column, for example, which was referred to as loading or structural index. As of 1958, the structural index approach to aircraft structural optimization was a highly developed and useful design tool. The method was, however, limited to simple components, a single loading condition and limited constraint conditions, further, the method was based on the "simultaneous failure mode design optimization method" which was inadequate from a design space point of view. Prior to 1958, the application of mathematical programming methods was limited to truss and plane frame type problems that could be formulated within the context of the plastic design philosophy. These applications considered a single load condition only. In 1958, Pearson, working within the plastic design philosophy, treated the minimum weight design of truss and frame structures subject to a multiplicity of distinct overload conditions. This work was important because of the innovative solution method employed. Essentially, the method employed was a precursor of structural analysis/synthesis where these are carried out simultaneously. The method also converted an inequality constrained optimization problem to an equivalent unconstrained minimization problem. Also, the dimensionality of the space was reduced by imaginative changes of variable. Pearson employed a method of random steps that used only function evaluations to find the minimum weight structure.

With his background in numerical structural mechanics and knowledge of mathematical programming techniques, it was Lucien A. Schmit who realized that minimum weight structural design could be viewed as an allocation of scarce resources and hence it should be possible to apply the methods of operations research to such problems. In a paper entitled: "Structural Design by Systematic Synthesis", presented in 1960, Schmit introduced the idea of coupling finite element structural analysis and non-linear mathematical programming to create automated optimum designs for a broad class of structural systems. In this paper, it was shown that a minimum weight design is not necessarily one in which each member is fully stressed in at least one of the load conditions. Thus, attention was drawn to the basic flaw in the simultaneous failure mode method. During the 1960's, first generation system level synthesis programs were developed based on joining finite element analysis and non-linear mathematical programming techniques. In 1968, in a paper by Morrow and Schmit entitled: "Structural Synthesis of a Stiffened Cylinder", the concept of using penalty functions to represent constraints was used. The constraint repulsion characteristic of the penalty function caused successive designs obtained during the synthesis to stay away from the constraints. This concept led to the idea that approximate analysis could be used during the synthesis. In later developments, the importance of reducing the number of analyses and derivative calculations was recognized. Various techniques were employed to improve the efficiency of the one-dimensional searches, and partial derivatives were only recalculated when the design moved outside some user-defined domain. The rapid development of the structural synthesis concept stimulated much interest in structural applications of mathematical programming techniques. Nevertheless, by 1970, it had become apparent that optimization techniques based on combining finite element analysis with mathematical programming techniques required unacceptably long computation times to solve practical problems. It was even suggested in academic circles that the mathematical programming approach to structural optimization was little more than an interesting research toy.

This depressing assessment led to re-newed efforts focused on fully stressed design concepts and optimality criteria methods for structural optimization.

While the concept of a Taylor space meant little to most structural designers, it was, however, recognized that in the design context, the objective of structural analysis should be to generate, with minimum effort, an estimate of critical and potentially critical response quantities to adequately guide the design. Developments in design oriented analysis included methods to obtain the rates of change of response quantities with respect to design variables (sensitivities), base vector methods for constructing approximate analyses, and efforts aimed at reorganizing the finite element methods to lend themselves better to the design optimization task. The introduction of approximation concepts using design variable linking, base vector methods, constraint screening and construction of high quality explicit approximations for retained constraints led to the emergence of mathematical programming based structural synthesis methods which were computationally efficient.

In 1973, Dr. Hirokazu Miura, while at UCLA, wrote a program called ACCESS-1. This program had a basic structure identical to that implemented later in MSC/NASTRAN SOL 200. This program was applied to wing-type structures, and convergence could be achieved in 5-10 analyses instead of hundreds or even thousands. After publication of the results obtained using this program, which used approximation concepts and mathematical programming, the optimality criteria community conceded defeat.

Dr. Claude Fleury (currently professor at University of Liege, Belgium) showed conclusively that the optimality criterion was a special case of the dual formulation of the optimization problem. All structural optimization methods developed after 1980 (with the exception of topology optimization based on homogenization methods) are based on mathematical programming.

3. Review of Current Methods in Application

The demands on the automobile designer to create a vehicle engineered to meet ever-increasing standards of safety, fuel efficiency, performance, and comfort represent a set of often-conflicting design targets. At present, there is no fully automatic method capable of creating an optimum vehicle design from these requirements. This task is left to the management and engineering skills of thousands of engineers and designers working within the automobile industry.

However, the quest for fuel efficiency, for example, has led to a requirement to reduce vehicle weight. Safety and comfort requirements dictate that the vehicle body be light, stiff and absorb impact energy in the event of collision. As the design evolves, engineers from each discipline may influence the design to meet their particular objectives.

Over the last 10 years, structural design optimization has become a widely accepted tool in the automobile industry. Finite element calculations to assess static strength or dynamic characteristics are routinely performed within structural synthesis software to obtain minimum weight structures that meet specified standards of strength and dynamic performance. This structural synthesis approach has been made possible on a routine basis by the availability of high performance computers and efficient state-of-the-art software. In the automobile industry, the analysis program MSC/NASTRAN is almost universally used as a de-facto standard for carrying out such calculations.

MSC/NASTRAN´s design synthesis capability incorporates the features required for efficiently performing optimization. The synthesis user interface is defined using a so-called design model. The analysis model is a conventional finite element model of the structure.

The essential features of the design model are that it must:

- Define the design variables to be modified and their acceptable bounds
- Describe the relationship between the design variables and the analysis model
- Define the objective function that provides a measure of the design quality
- Define limits (constraints) on design responses for each analysis discipline

The design model is a true mathematical abstraction and is completely open to user definition. It has no unique or definite form. Intelligent formulation of the design model is the key to successful application of the structural design synthesis capability in MSC/NASTRAN.

A powerful feature of design optimization in MSC/NASTRAN is that the synthesis may be performed with the structure subjected to a number of different analysis types for a number of loading and support conditions. The results of all these analyses are considered simultaneously by the optimizer when proposing an improved design. For example, a static torsion load on the body and a frequency dependent dynamic loading at the engine mounts may be applied with static and dynamic response limits. The resulting minimum weight design proposed by the optimizer thus satisfies both the static and dynamic response constraints simultaneously. The analysis disciplines that can be currently applied include statics, normal modes analysis, buckling analysis, direct and modal frequency response analysis and modal transient analysis. Internal acoustic analysis may also be selected in dynamic solutions.

The MSC/NASTRAN design synthesis capability incorporates full use of approximation concepts, including design variable linking and basis vector concepts, response constraint screening and load case deletion for inactive constraints, efficient sensitivity coefficient calculations and high quality explicit approximations for the objective and constraint functions. Several optimization algorithms are available. Typically, convergence to an optimum is achieved within 5 -10 iterations through the analysis.

For NVH optimization, forced response analysis and sensitivity calculations must be performed at even hundreds of excitation frequencies. With the large models used in practice, this class of optimization problem revealed two important areas of inefficiency in MSC/NASTRAN standard V68. To overcome these inefficiencies, modifications were made to standard MSC/NASTRAN. In particular, the modifications included the addition of the so-called adjoint load method and replacement of the DVSG1 module by an external program in which the data traffic was organized as efficiently as possible to deal specifically with forced response design sensitivity. The modified version of MSC/NASTRAN became known as V68X, and was a joint development effort between CDH GmbH, Cray Research Corporation (now SGI) and the MacNeal Schwendler Corporation. Many of the advantages of V68X are now available in standard MSC/NASTRAN V70.5.

4. Applications of Structural Optimization in Vehicle Dynamics

The purpose of this section is to discuss a few highlights related to the application of structural design optimization in everyday engineering practice, with particular reference to vehicle comfort dynamics.

The application of this tool requires a new approach to improving the dynamic behavior of a vehicle structure; therefore, it will be helpful to also describe the standard method of proceeding.

Corresponding to the various phases of vehicle design, analysis activities fall roughly into three categories:

- Preliminary design studies in the concept phase
- Detailed assessment of a given concept following elimination of concept alternatives
- Tuning of an almost finalized design

The detail of the finite element models used in the above categories is obviously related to the information available to the analyst. In the concept phase, the models are necessarily coarse, but must, at least, contain enough information to guide decisions between concept designs. These models are abstract in nature and require significant engineering skill to create and to interpret the results. When the design is almost finalized, the models are large and detailed with accuracy appropriate to the fine tuning activities. Although the issue of model quality is critical to successful analyses, it will not be discussed here.

The primary purpose of engineering analysis is to obtain results for the response of a structure to certain imposed conditions, or loads, with appropriate boundary conditions. The loads, representative of in-service operating conditions, used in the prediction of the dynamic behavior of an automobile are:

- Engine idle loads (rotating mass and gas pressures)
- Tire/wheel unbalance
- Road excitation
- Drive line unbalance

Using full vehicle, low-frequency NVH CAE models, these loads are used to predict and assess, for example, the vehicle's shake and boom response at various locations in the vehicle. The types of analysis used to investigate the vehicle's behavior are usually: normal modes analysis (eigenanalysis) and forced response analysis over a range of frequencies. Also, for some specific cases, time-domain response analysis may be necessary. In the context of MSC/NASTRAN this requires application of SOL103, SOL111, and SOL112, respectively.

The standard procedure to analyze a given vehicle concept requires the following general steps:

- Eigenvalue analysis of the full vehicle followed by frequency response analysis with a single load or a set of load combinations
- Identify peaks (and their related frequencies) in the response spectrum that exceed the prescribed limits, animation of responses (structural deformations and pressure distributions at selected frequencies), analysis of structural and acoustic modal participation
- Interpretation of analysis, to understand structural and acoustic behavior
- Identification of candidate design changes likely to improve structural dynamic behavior

While the first three steps serve as means to understanding the dynamic behavior, the final step is an exercise in interpretation of the frequency spectrum. Design changes are then tested by repeating the first three steps. The procedure is, essentially, a manual trial-and-error parameter adjustment technique that is guided by the experience and skill of the engineer.

In contrast to the standard procedure described in the foregoing, design optimization attempts to automatically synthesize an improved structure, given a set of candidate variables, selected, a priori, by the analyst, an objective and constraints (the design model). The essential features of the calculation process are:

- Determination of the structural response for the initial configuration
- Finding the response sensitivity of user-selected components
- Generation of an approximate mathematical model
- Engaging an optimization algorithm to automatically change the parameters.
- Repeat process using new design parameters suggested by the optimizer algorithm.

If successful, this iterative procedure converges to yield an improved structural behavior.

The following examples will show the application of frequency response optimization. The first example is focused on the improvement of steering wheel vibration in the engine idling condition. The next example relates to the reduction of undesired noise influence on the passengers, partially induced by engine excitation.

4.1 Example Applications

Example 1: Reduction of steering wheel vibration by frequency response optimization

This example relates to a case where it was required to achieve acceptable steering wheel vibration levels by making structural changes to the steering system and its connections to the car body. Changes to the car body were not allowed because the global stiffness of the naked car body – characterized by its eigenfrequencies – was already optimized and satisfied prescribed design targets.

In order to predict the structural behavior in a late stage of development where test results are available, a high quality system model (vehicle body, engine, power train, suspension, etc.) is a prerequisite.

The first step was to apply classical analysis tools like normal modes analysis, frequency response, and frequency deformation analysis in order to understand the behavior of the system. The next step was to define the design variables relating to the region which was permitted to change within prescribed limits taking into account fatigue, crash, and production requirements.

Calculation of the design sensitivities was used to determine which of the variables had a strong influence on the vibration behavior. The final and the most important step was to carry out the actual optimization.

The result of the optimization process is presented in the diagram, which shows the original response behavior (please refer to presentation). An impression of the model quality is given by the comparison with a corresponding test curve. Further, the calculated response curve for the final design – found by optimization – is given and compared to test.

Example 2: Reduction of noise pressure level by frequency response optimization

It is a fact that the basic acoustic quality of a car is determined in the early stages of development. A careful layout of all components, from a dynamics point of view, is a required condition to achieve an acceptable acoustic behavior. This must be carried out very early in the development process, because only then is there a chance to influence the conceptual design layout.

Optimization is an instrument ideally suited to this task. As in the above example, the necessary condition is that the model is of sufficient quality required to describe the most important dynamic effects in the frequency domain of interest. In addition to the car body, the engine, the power train, suspension, etc., must be modeled in sufficient detail to accurately describe the important dynamic effects.

Before beginning the optimization process, analyses of the acoustic behavior of the passenger compartment, using modal methods and a frequency response analysis of the coupled system subject to engine excitation were carried out. Additionally, the structural grid point participation was investigated in order to understand the influence of various body panels surrounding the passenger compartment on the interior sound pressure levels in the frequency range of interest.

A set of design variables considered to influence the acoustic behavior in the frequency domain of interest was then selected by a group of body structural design engineers – including representatives from crash, fatigue, and the dynamic and acoustic groups.

The diagram (*please refer to presentation*) shows the measured as well as the computed results for the initial design. The goal was to decrease the sound pressure level in a selected frequency range by realistic car body modifications. The result of the optimization procedure based on the selected 110 design variables shows that there is a tremendous improvement in the sound pressure level. This improvement was approximately achieved in the actual prototype vehicle.

5. Future Prospects

To date, the scope of application of structural optimization has been limited mainly to automatic adjustment of steel plate thicknesses and stiffness of mounts to control structural responses predicted by linear structural analyses. There are many other tasks required in the design of a vehicle at the various stages of product development. Some of these tasks will necessarily depend only on creative and flexible human cognitive capabilities. Automatic design synthesis procedures could, however, be used for a wide range of tasks. It is difficult to predict the long-term future of structural optimization in the automotive industry, but the following list includes the most plausible near-future candidates.

- Extend its applicability to responses involving non-linear analyses. The most important candidate is crashworthiness. Kinematics and fluid dynamics are also deemed important.
- Applications to subsystems and their component parts design; for example, engine and tire radiated noise optimization.
- Applications to the design of structural geometry (shape). This subject is substantially more difficult but more effective in many cases than adjustment of plate thicknesses. Perhaps development of robust automatic mesh generation directly from a parametric CAD model will be the key technology.
- Topological design of structural arrangement. This technology will be most effective when applied to the conceptual design stage.
- Design optimization with multi-disciplinary analyses. Already, structural and acoustic analyses are considered simultaneously in the NVH design. In the near future, requirements of crashworthiness will have to be incorporated in the NVH design optimization. There are whole series of innovative design strategies conceived in this category.
- Design Optimization with discrete variable algorithms.

Innovative application of design optimization methods will be able to provide high quality data that will be directly useful in making appropriate design decisions and in some cases to stimulate the creation of innovative design concepts. Finally, future use of optimization methods will be influenced by developments in computer hardware as well as software, because there is no doubt that these increasingly complex applications demand high processing power and flexible interface to the human engineers. Cost-performance will be a continuing issue in selecting appropriate computing platforms to provide adequate service.

While gradient based optimizer methods will continue to be used in the future, these methods are limited to local exploitation of the design space. Exploration is fundamentally different from exploitation. Exploration implies searching in the entire design space. This search cannot be exhaustive since there are simply too many dimensions and potentially enormous computation costs. Instead, it will be necessary to rely on some probabilistic and heuristic knowledge to sample the design space and make judgements about what might be a fruitful area in which to search further. It is likely that the future search for global optimum in large scale multiple analysis discipline structural design problems will require evolutionary algorithms, knowledge-based systems, and very intelligent reductions of the design space.

6. Conclusions

This paper has presented an historical review of structural optimization methods. The current state of the art has been described with particular reference to the methods in use within the automobile industry. Several applications have been discussed where the optimization tools have been successfully applied to realistic vehicle structural dynamics and acoustic design challenges. Suggestions have been made for the future developments of structural optimization methods. The availability of structural optimization tools is, undoubtedly, of great potential help to the designer. It must, however, be emphasized that creativity and human intervention are the primary ingredients in the recipe for success. Perhaps the complex interaction between a structure's components, when several design variables are involved, is too difficult to comprehend. Thus any implicit knowledge may be impossible to extract from the results of a successful optimization exercise. For this we must rely on the computer. On the other hand, the formulation of the design model requires human creativity and ingenuity. This activity does, however, require an understanding, at least at an intuitive level, of the underlying design landscape. The use of optimization as an exploration tool should be actively encouraged. The task will change from a local search for an improved design to a global search for attractive topologically alternative designs. Because of the inordinate computation times implied by an exhaustive search, we must abandon concepts such as convergence and global optima. The question will be: "how much are we, in given time, prepared to invest in computation resources, in the hope that we obtain an adequate return on our investment? ". This is a new view of computing.

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